

# **Electrokinetic Flow Control and Propulsion for MAVs**

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**MAV Workshop**

**Micro Aerial Vehicles –  
Unmet Technological Requirements**

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# Aerodynamics of Micro Aerial Vehicles

- Micro Aerial Vehicles (MAV) operate at chord Reynolds numbers below 200000
  - Early laminar flow separation at the leading edge
  - Compact geometry (low aspect-ratio below 2) gives rise to strong 3D effects
- Nonlinear lift characteristics and low aerodynamic efficiency
- MAVs supported from overdimensioned propulsion and are „hanging“ on the thrust vector

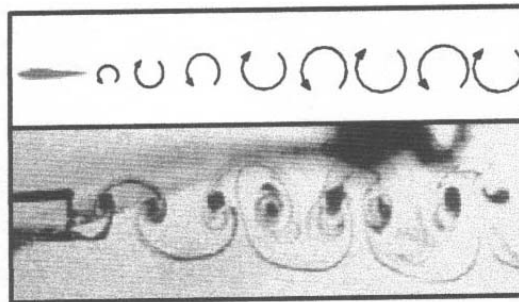
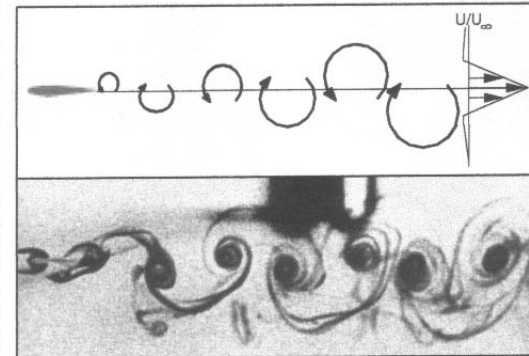
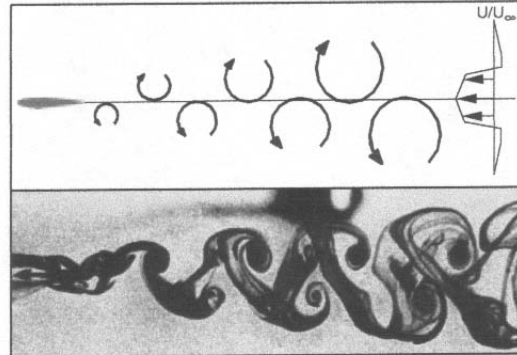
Which possibilities for active flow control are available to improve Flight performance of Micro Aerial Vehicles?

# **Possibilities for Active Flow Control**

# 1. Unsteady Lift und Propulsion Using Flapping Wing (Mechanical Wave Propulsion)



Ornithopter-Flightmodel from Prof. DeLaurier (Source: Uni Toronto)



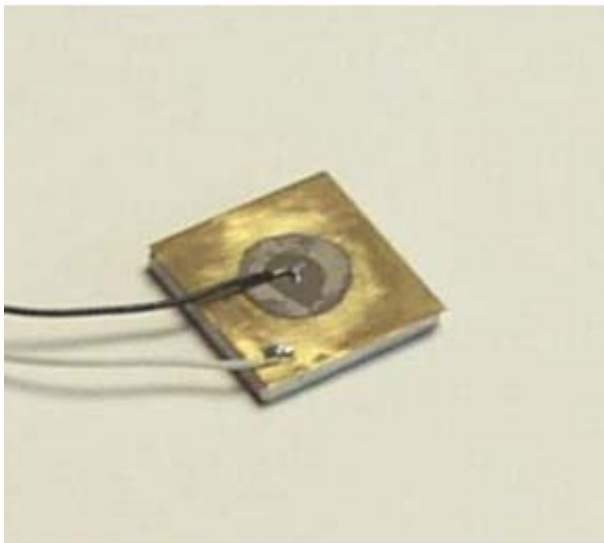
Vortex Street for Drag, Thrust and Zero Drag (Source: Jones, K. D.)

See for further references: <http://www.ism.tu-bs.de/WRLD/mneef/neef.html>

Jones, K. D.; Castro, B.M.; Mahmoud, O.; Pollard, S.J.; Platzer, M.F.; Neef, M.F.; Gonet, K.; Hummel, D. (2002) A collaborative numerical and experimental investigation of flapping-wing propulsion. AIAA Paper 2002-0706, 40th Aerospace Sciences Meeting & Exhibit, Reno, NV.

## 2. Active Flow Control Using Piezoelectric Synthetic Jet Actuators

Unsteady Excitation of the Laminar Boundary Layer Using Piezoelectric Actuators at  $f = 250$  Hz



Bottom view of the piezoelectric synthetic jet showing the actuator side and lead wires

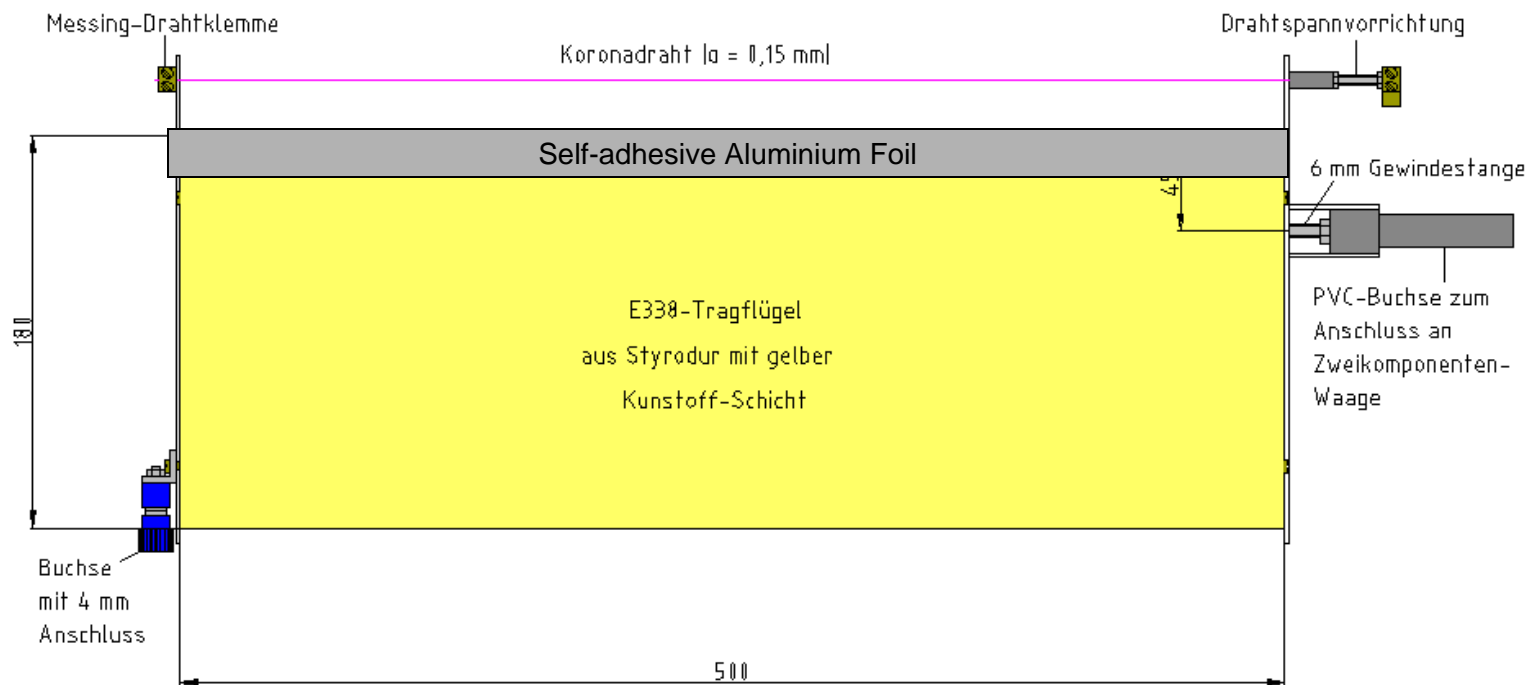


NACA 0012 wind tunnel specimen with integrated piezoelectric synthetic jet actuators

Source: <http://www.spa-inc.net/smtmemstest.htm>

### 3. Active Flow Control Using Electrostatic Fields

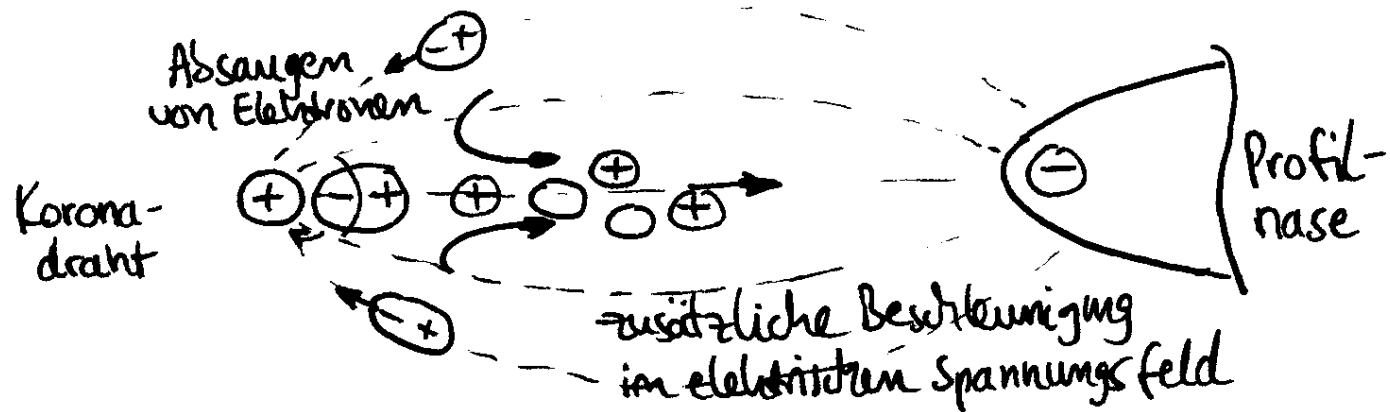
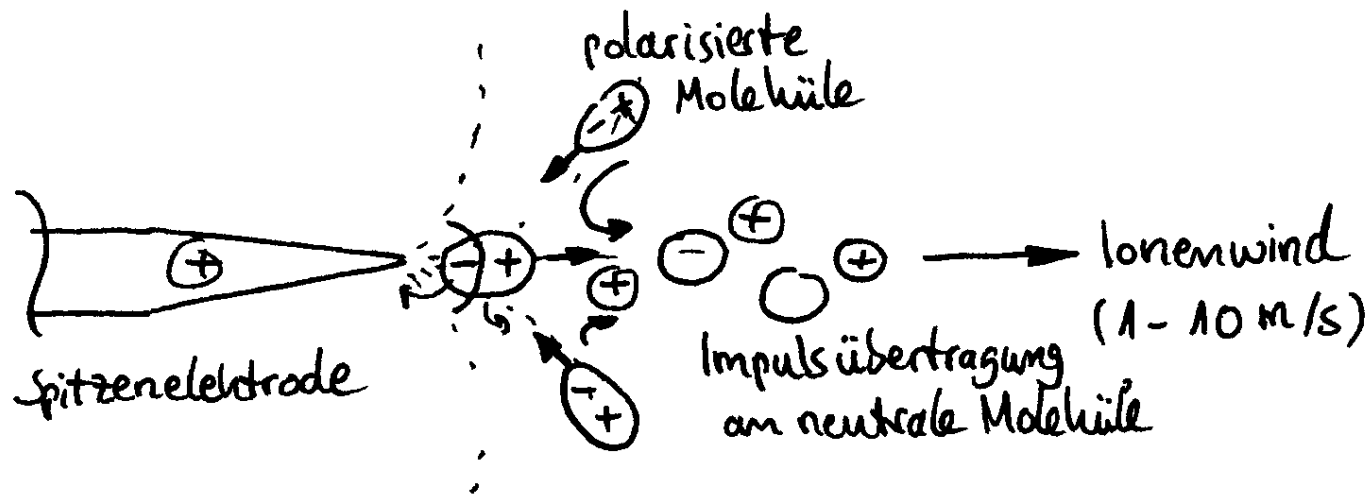
Acceleration of weakly-ionized air in electric tension fields to stabilize the laminar boundary layer



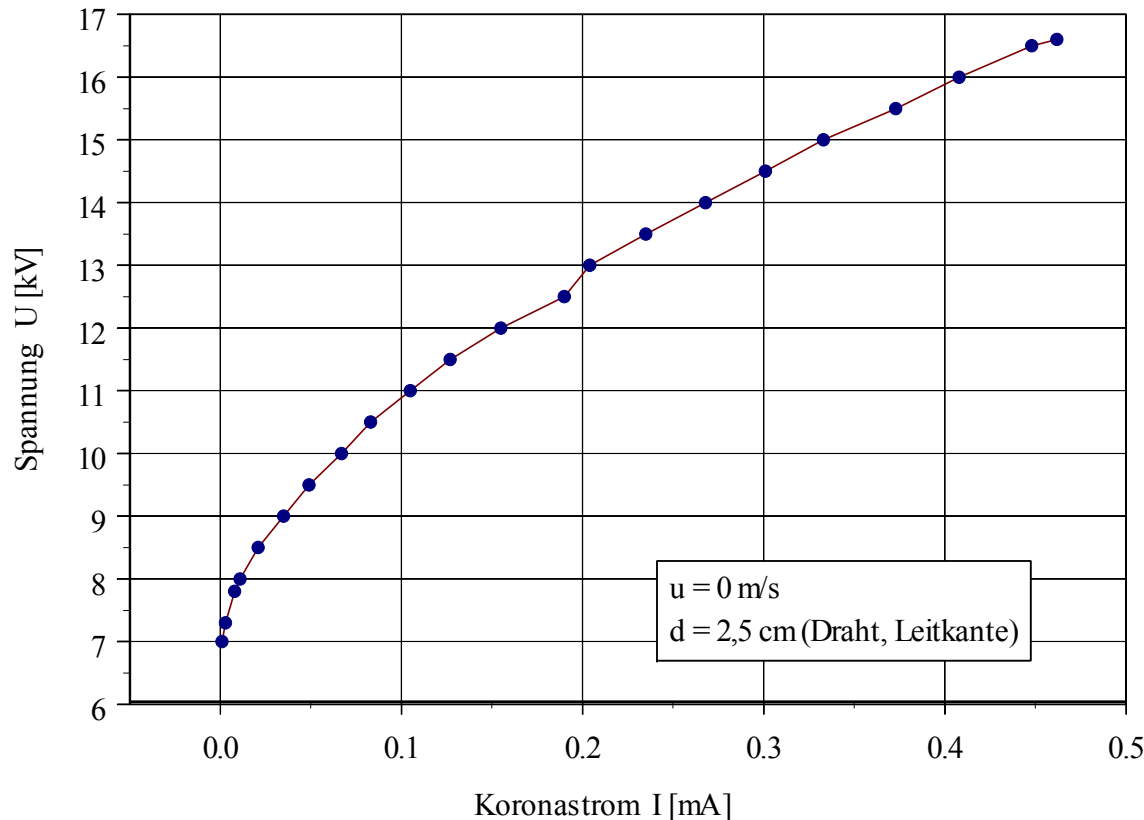
Speed Range in Experiments: 1,1 - 11,0 m/s  
Chord Reynolds Number Range: 13250 - 132500



# Mechanism of Air Ionisation around Corona Wires



# Current-Voltage Characteristics for Corona Wire with Diameter $a = 0.15 \text{ mm}$



Current-Voltage Characteristics for Corona Wire with Diameter  $a = 150 \mu\text{m}$  and Electrode-Distance  $d = 25 \text{ mm}$  to Leading Edge at Zero Air Speed.

At Constant Wire Diameter the **Ionic Wind Velocity** is *proportional* to **Square Root of the Corona Current**.

## Electrical Power per 50 cm Wire:

$I = 0,48 \text{ mA}$ ,  $U = 16,5 \text{ kV} \rightarrow P = 7,9 \text{ Watts}$

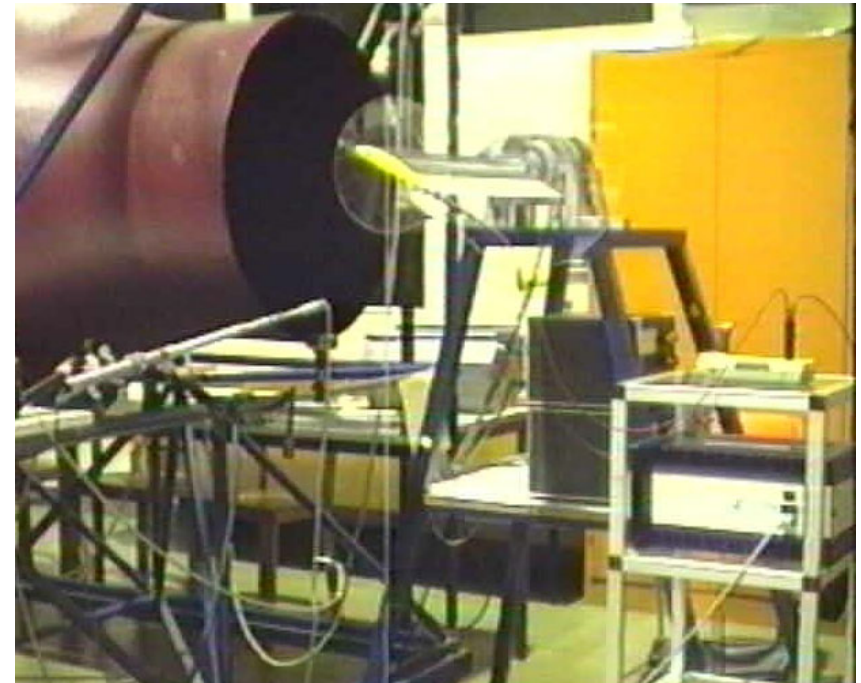
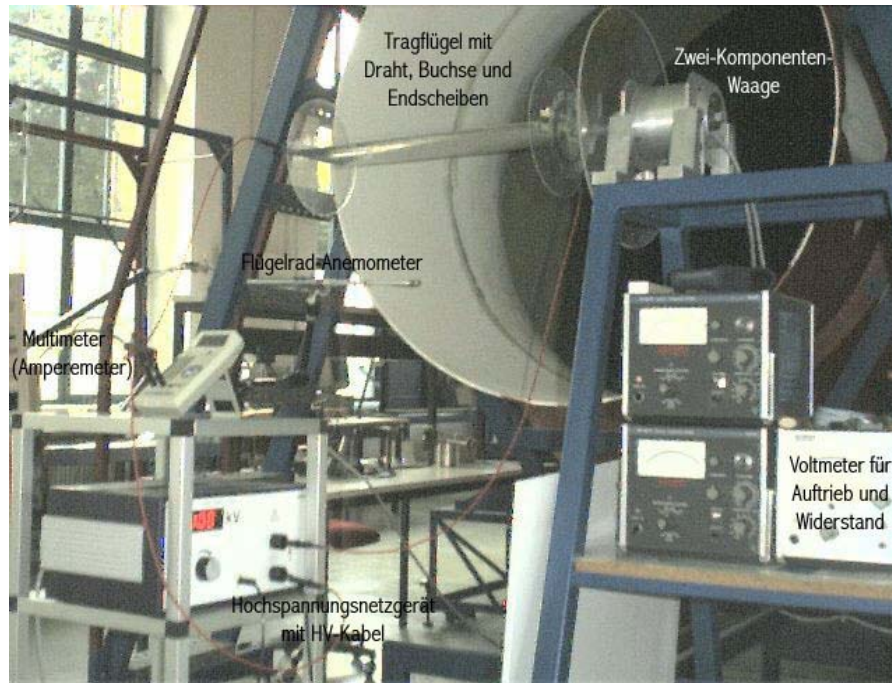
$I = 0,30 \text{ mA}$ ,  $U = 14,4 \text{ kV} \rightarrow P = 4,3 \text{ Watts}$

$I = 0,24 \text{ mA}$ ,  $U = 13,4 \text{ kV} \rightarrow P = 3,2 \text{ Watts}$

## Goal for MAV-Application:

As small as possible fine micro pikes to reduce power at constant corona current.

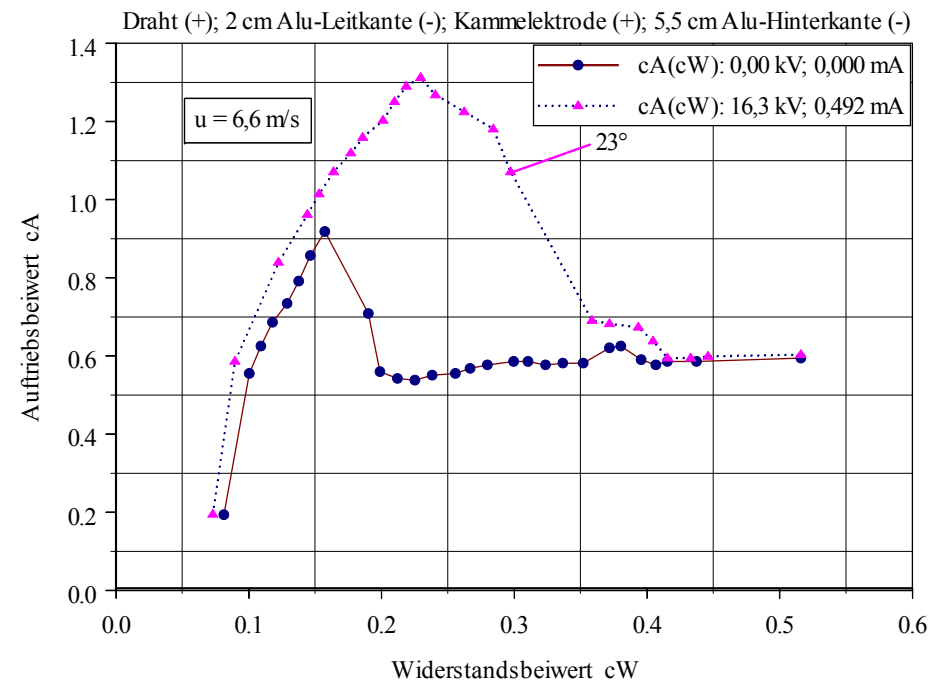
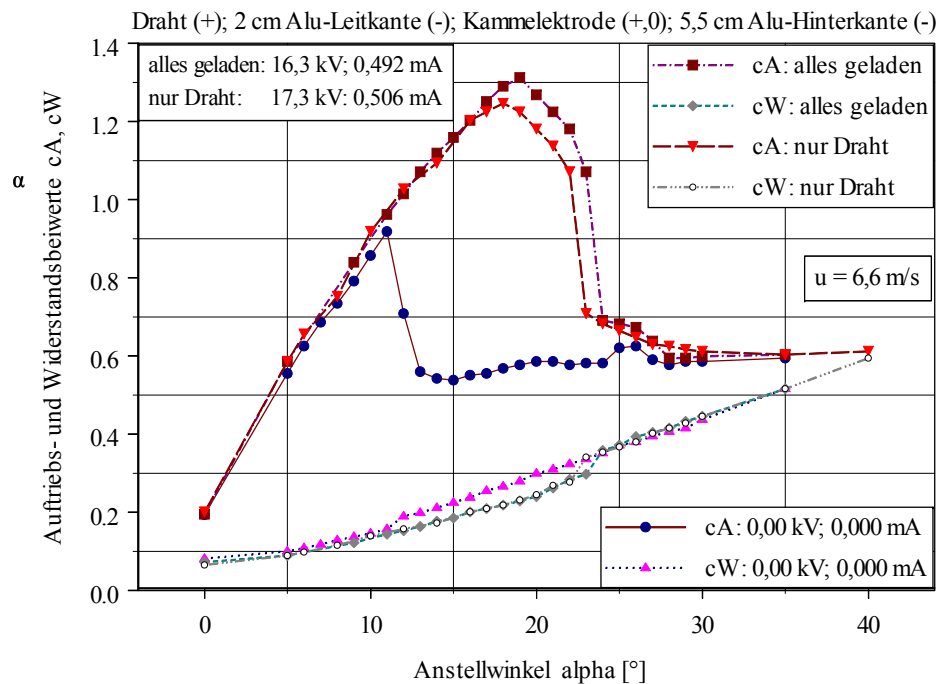
# Experiment Set-Up at the Institute of Bionics, TU Berlin



<b>Grand Wind Tunnel</b> with Outlet Nozzle $d=1200$ mm.	<b>Small Wind Tunnel</b> with Outlet Nozzle $d=600$ mm.
Minimal Speed: 5 m/s	Minimal Speed: 0 m/s
Maximum Speed: 15 m/s	Maximum Speed: 6 m/s

# Separation Delay and Lift Enhancement at $u=6,6$ m/s

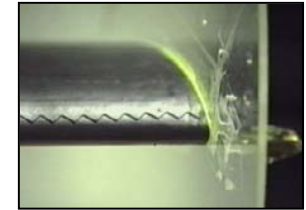
- Lift Enhancement at  $\alpha = 19^\circ$  is 127%
- Drag Coefficient decreases by 18%  
→ Increase of Aerodynamic Efficiency by 177%
- At  $\alpha = 0^\circ$  with E-Field Drag Reduction by 10,1 %



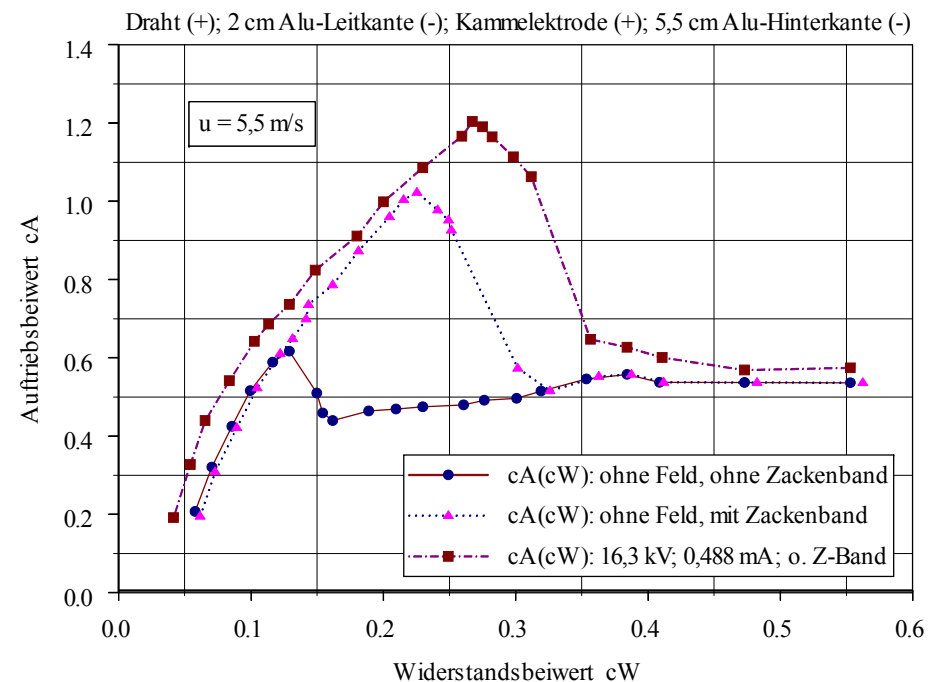
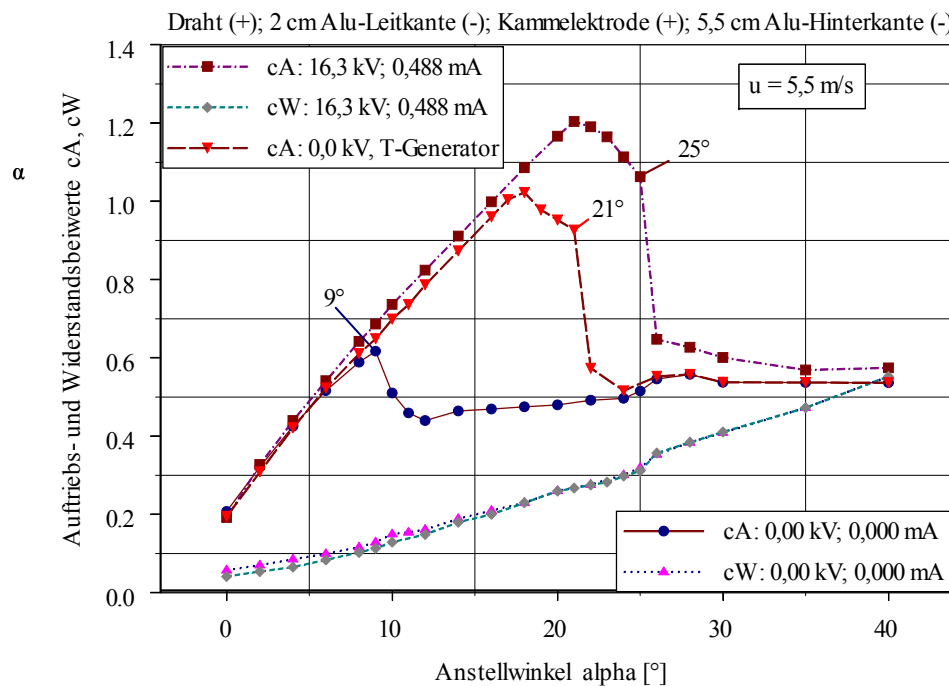
Additional Electrode Pair at Trailing Edge has Effect of Jet Flap.

# Separation Delay and Lift Enhancement at $u=5,5 \text{ m/s}$

- Turbulator delays laminar separation up to  $\alpha = 21^\circ$ .
- But:
  - max. lift coefficient 15% lower than with corona discharge
  - drag increase at critical angles of attack
- At  $\alpha = 0^\circ$  drag coefficient increase by 6,6 %.
- Degradation of aerodynamic efficiency by 11,8%



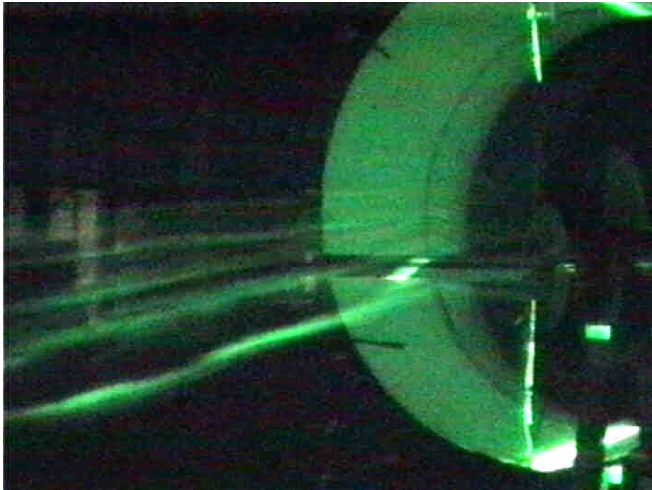
Turbulence Generator



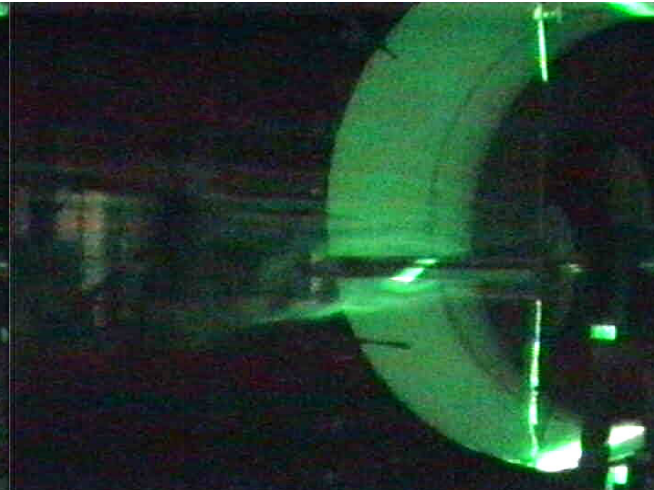
At  $\alpha=0^\circ$  with Corona Discharge (without Turbulator) Decrease of Drag Coefficient by 28%.



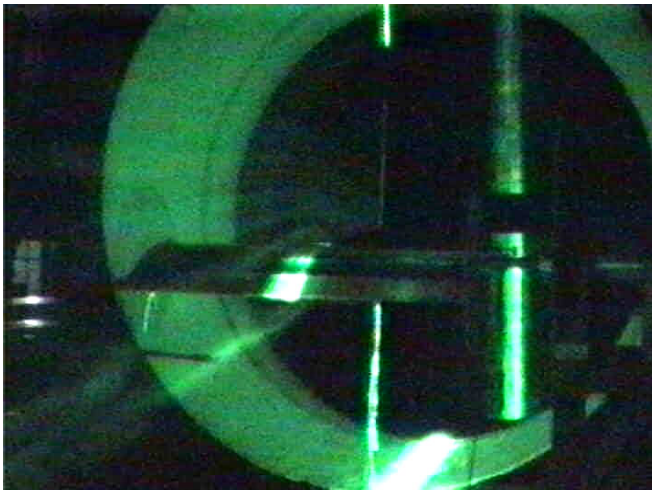
# Laser-Light-Sheet Smoke Wire Visualisation



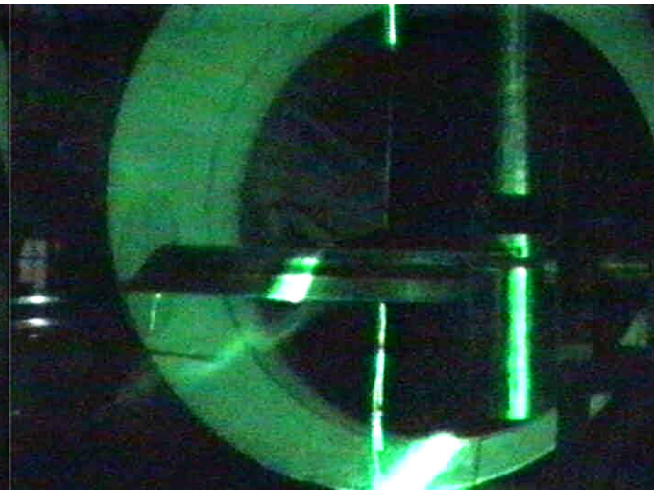
$\alpha = 12^\circ$ ;  $u = 6,6$  m/s;  $U = 16,3$  kV;  $I = 0,492$  mA



$\alpha = 12^\circ$ ;  $u = 6,6$  m/s;  $U = 0,00$  kV;  $I = 0,000$  mA



$\alpha = 20^\circ$ ;  $u = 6,6$  m/s;  $U = 16,6$  kV;  $I = 0,497$  mA

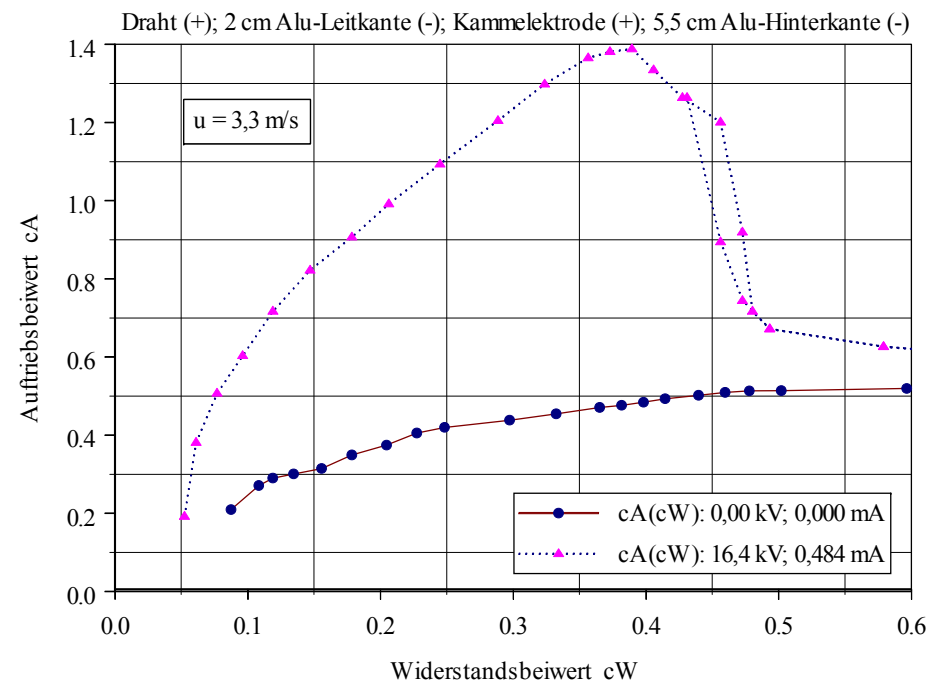
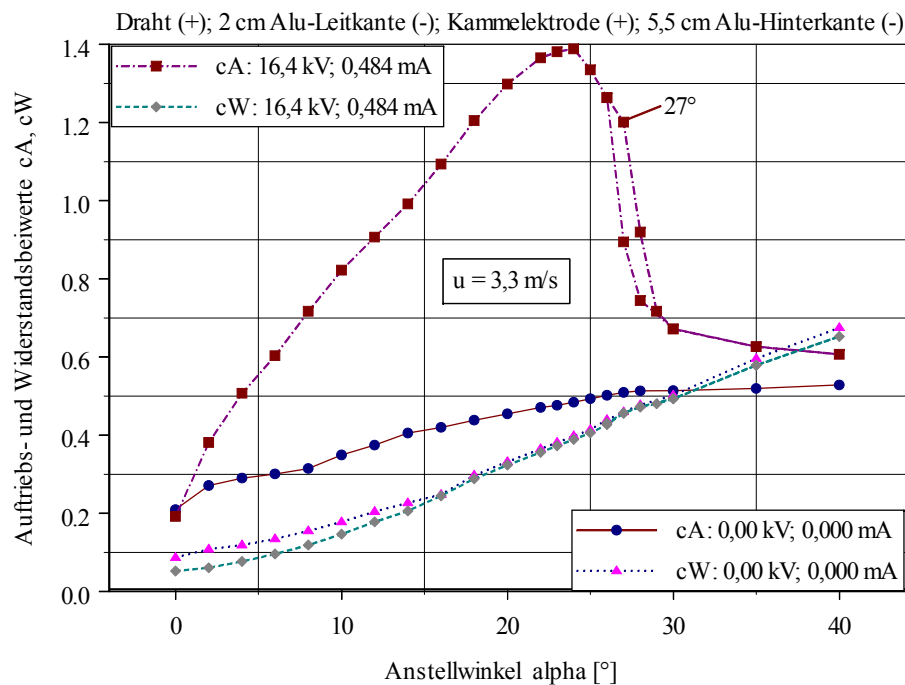


$\alpha = 20^\circ$ ;  $u = 6,6$  m/s;  $U = 0,00$  kV;  $I = 0,000$  mA

Up to  $\alpha = 15^\circ$  like in a fluidic flip-flop-switch flow can be separated, reattached and again separated (see video presentation).

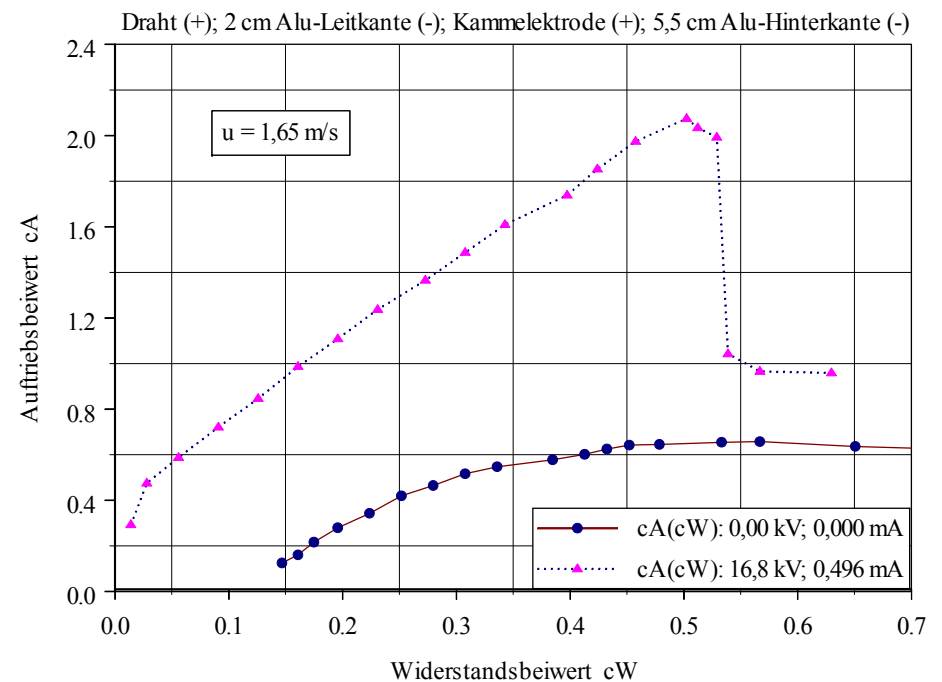
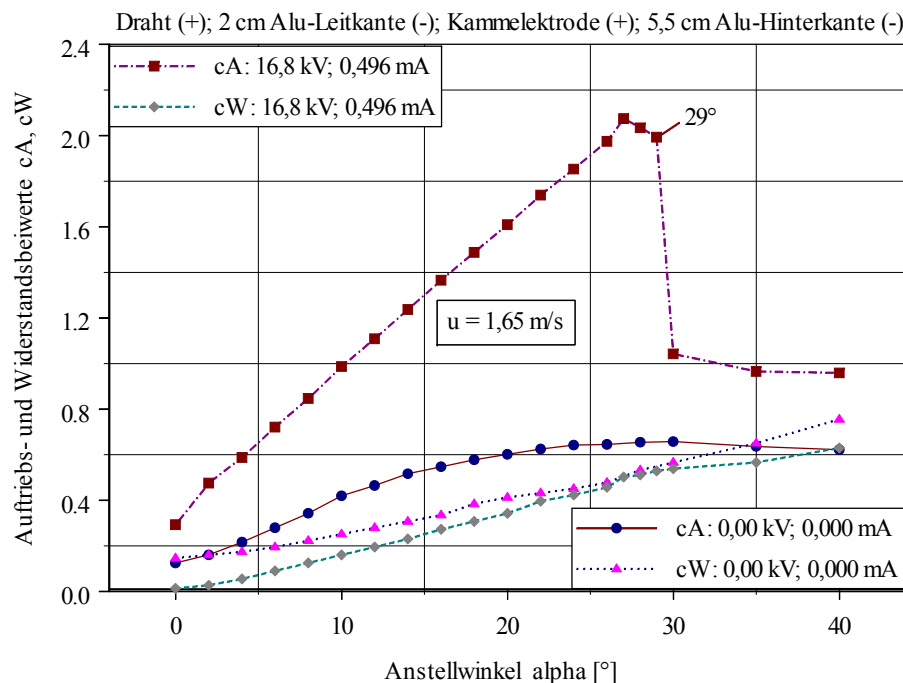
# Separation Delay and Lift Enhancement at $u=3,3$ m/s

- at  $u = 1,1 - 4,4$  m/s Turbulator without Effect on Laminar Flow Separation
- Corona Discharge shows dramatic Effect on Lift and Drag Coefficient
- at  $\alpha = 23^\circ$  maximum Lift Coefficient Enhancement by 191%
- at  $\alpha = 0^\circ$  Drag Coefficient Reduced by 40%
- at  $\alpha = 4^\circ$  Aerodynamic Efficiency Increased by 170% and at  $\alpha = 8^\circ$  by 198%



# Separation Delay and Lift Enhancement at $u=1,65$ m/s

- at  $\alpha = 27^\circ$  maximum Lift Coefficient Enhancement by 220% ,  $cA_{\max} = 2,07$
- at  $\alpha = 0^\circ$  Drag Coefficient Reduced by 90,5%  
Lift Coefficient Increased by 133%  
→ Increase of Aerodynamic Efficiency by 2350%



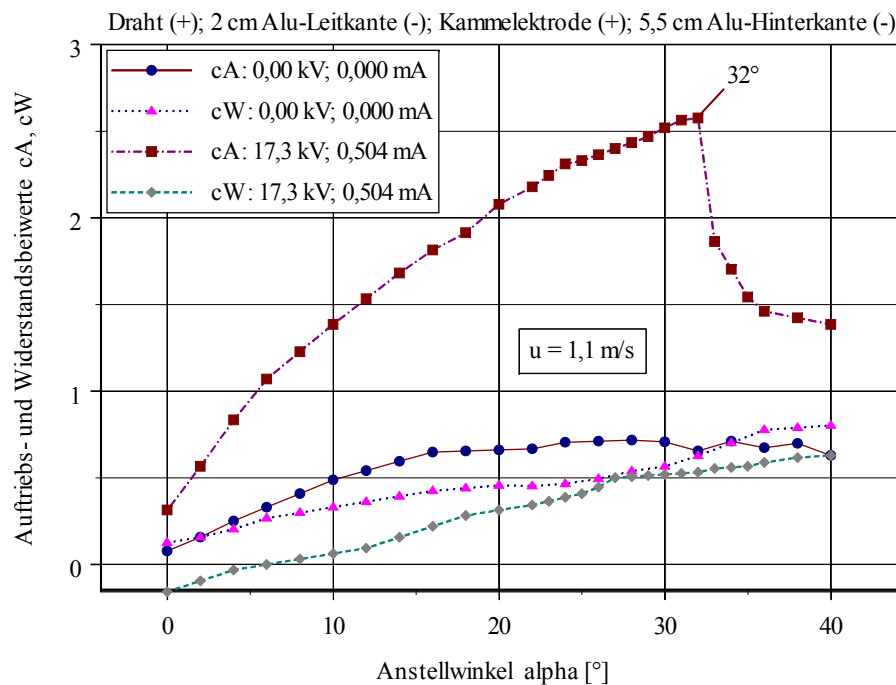
Ionic wind generates additional circulation (super circulation) by Acceleration on Suction Side.  
Ionic wind velocity now in the range of wind tunnel air velocity.



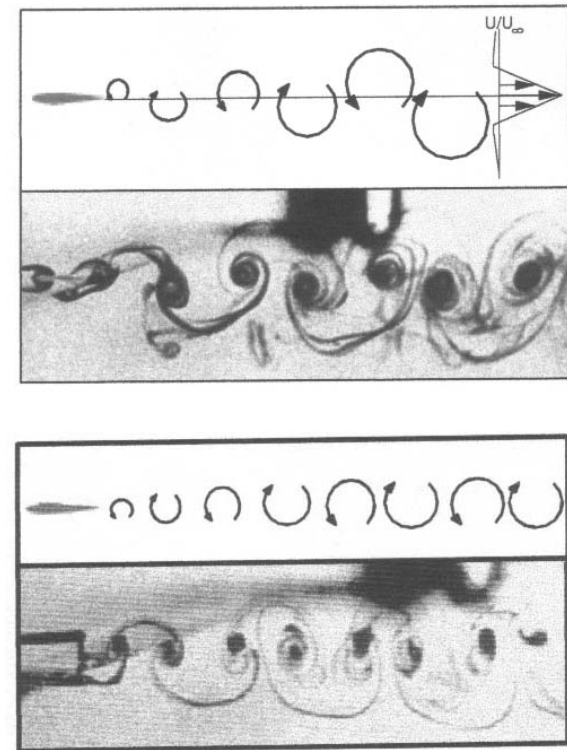
# Separation Delay and Lift Enhancement at $u=1,1$ m/s

- at  $\alpha = 32^\circ$  Lift Coefficient Enhancement by 293%, maximum Lift Coefficient of 2,57
- at  $\alpha = 0^\circ$  Drag Coefficient even Reduced by 113%

→ Wing Generates Thrust up to  $\alpha = 6^\circ$ !!

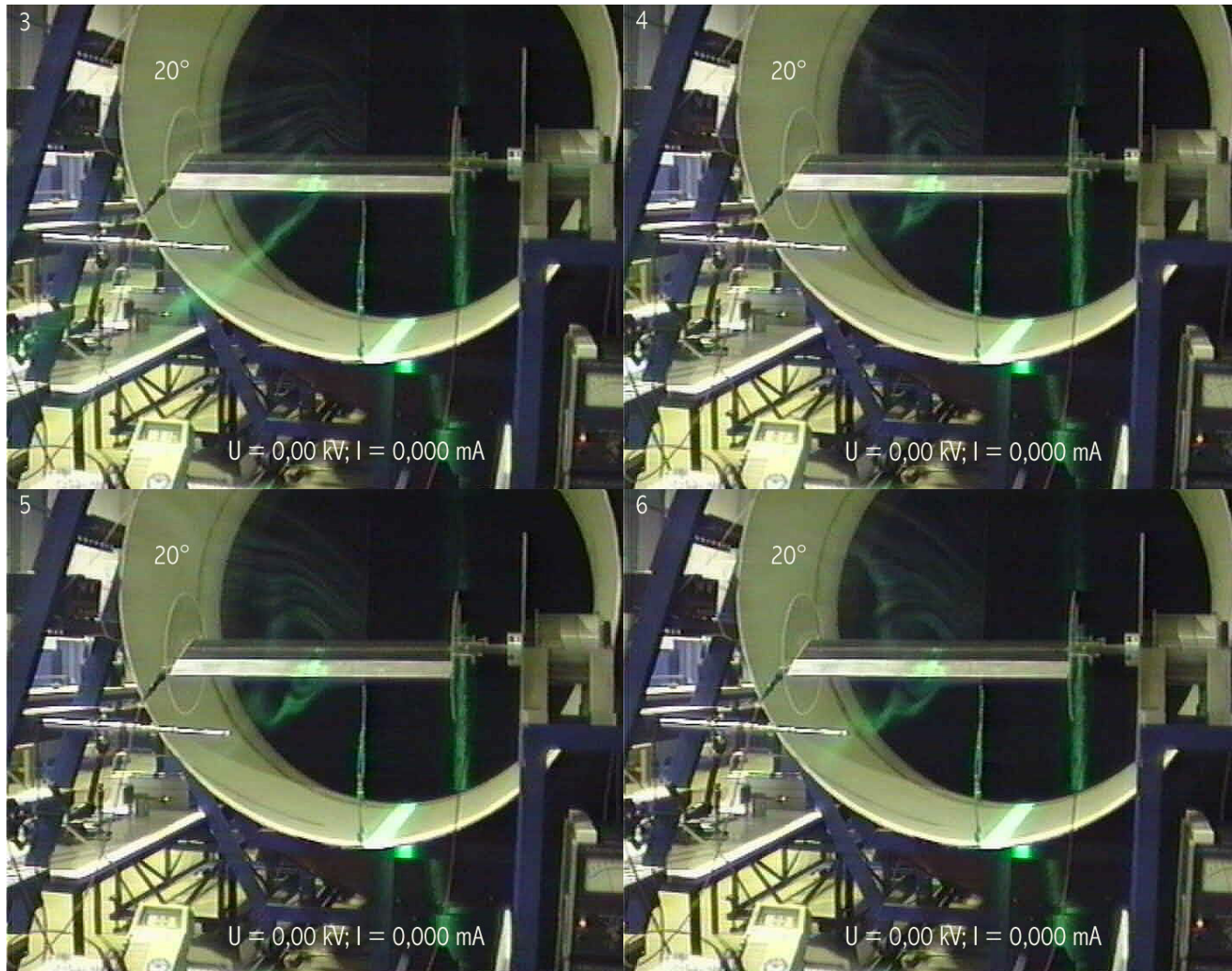


Ionic Wind Velocity > Wind Tunnel Air Velocity



Vortex Street with Thrust and Zero Drag (Source: Jones, K. D.)

# Picture Sequences to Smoke Wire Visualisation



Controlled separation can be used to study nature of vortex generation.

# Video Presentation

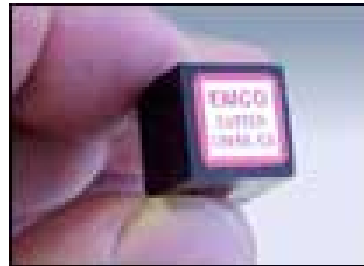
[electrofluid1.avi](#)

(see also <http://www.bionik.tu-berlin.de/user/goeksel/electrofluid1.htm>)

# Outview

# Miniaturised High Voltage Power Supplies

For Micro-UAVs:



Q-Serie:

0 to +/-5,000 VDC 0,5 Watts

Weight: 4,25 g

0 to +/-10,000 VDC 0,5 Watts

Weight: 28,3 g

For Mini-UAVs:



E-Serie:

0 to +/-12,000 VDC 3 Watts

Weight: 85 g



F-Serie:

0 to +/-12,000 VDC 10 Watts

Weight: 142 g

Source: <http://www.emcohighvoltage.com/>

# Miniaturised Field Electron Emitter

## Cold Field Electron Emission from Microstructured Surfaces (Fowler-Nordheim Tunnel Effect):

- Adoption of Organic Surface Films from Carbon Nano Tubes
- Adoption of Microstructured Metal-Sheets with Carbon-Shield (Fullerenes or amorphe Diamond-Layers)

→ At low high voltages already emission rates of more than 3 mA/cm<sup>2</sup> achievable (compare Basic Research Experiments with Corona Wire with maximum Current Density of 0.5 mA/2.4 cm<sup>2</sup>).  
(Highly Energetic Diamond Emitter even reach kA/cm<sup>2</sup>.)

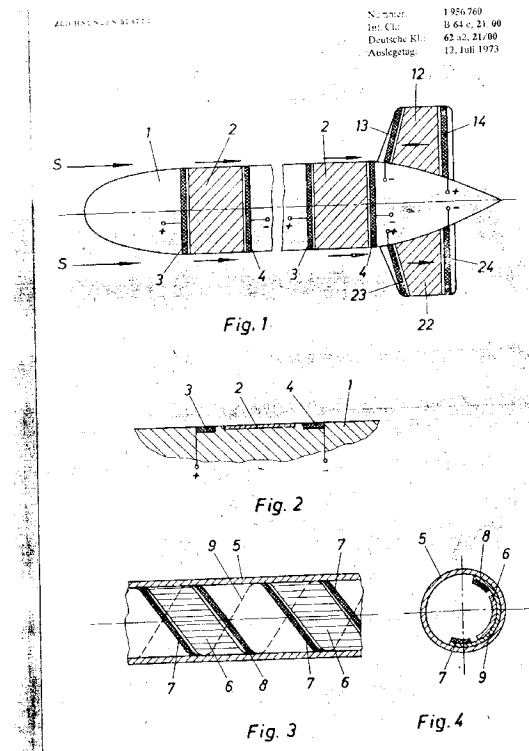
Key Words: Field (Electron) Emission, Multi-Wall Carbon Nanotube Films, Emitting Diamond Films, Microfabricated Emitters, Carbon Cold Cathode, Solid State Emitter

# Miniaturised Field Electron Emitter

- Self-activation of cold field electron emission on suitable surfaces through natural friction charging and turbulence in the boundary layer.
- Formation of Electric Double-Layers, which could be moved by use of electric voltage field actuators.

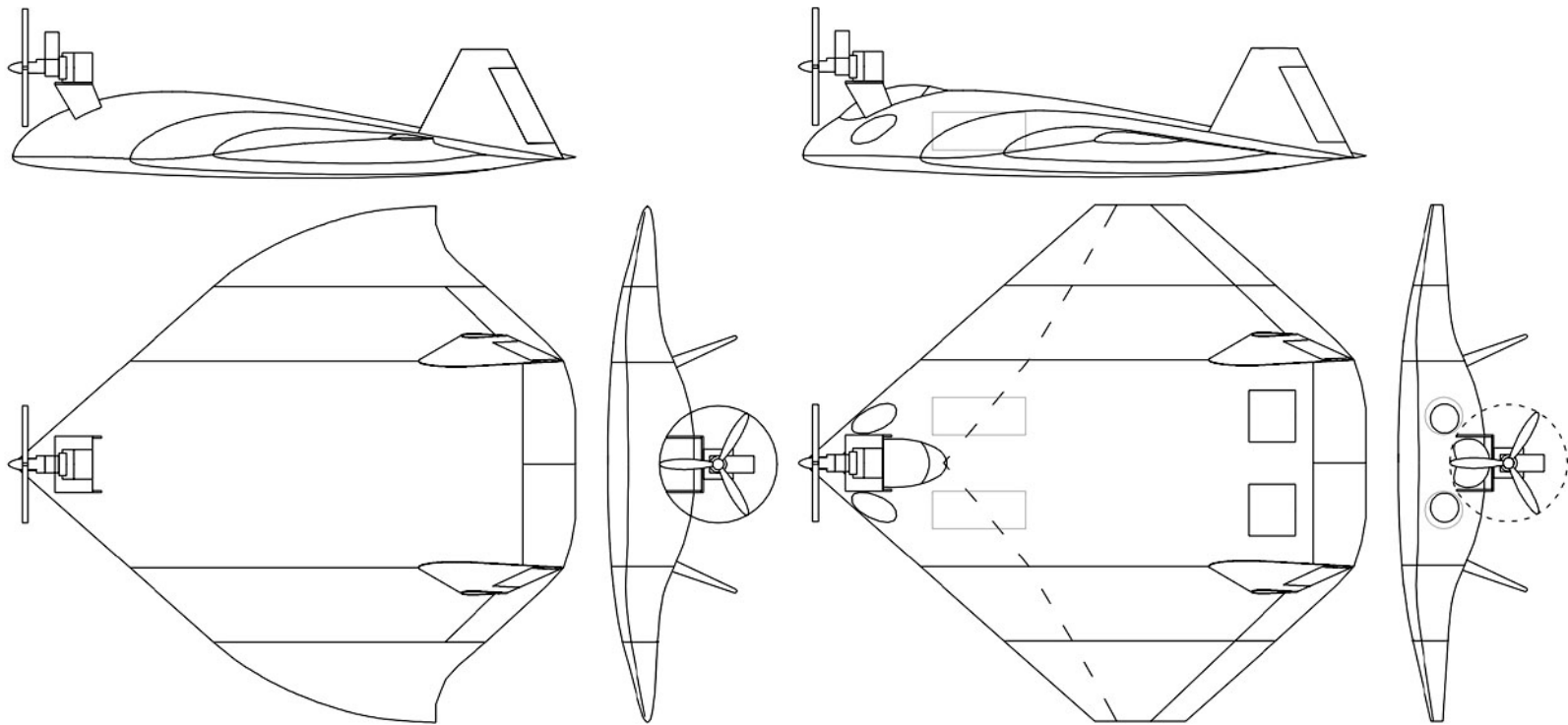
See also Patent of Mr. Donatus Dornier,  
Dornier System GmbH

German Patent 1956760 (7th February 1974)  
„Einrichtung zur Beeinflussung der  
Grenzschicht eines Strömungsmittels“



# Mini Aerial Vehicle as Compact Demonstrator

Wing Airfoil: Eppler E338

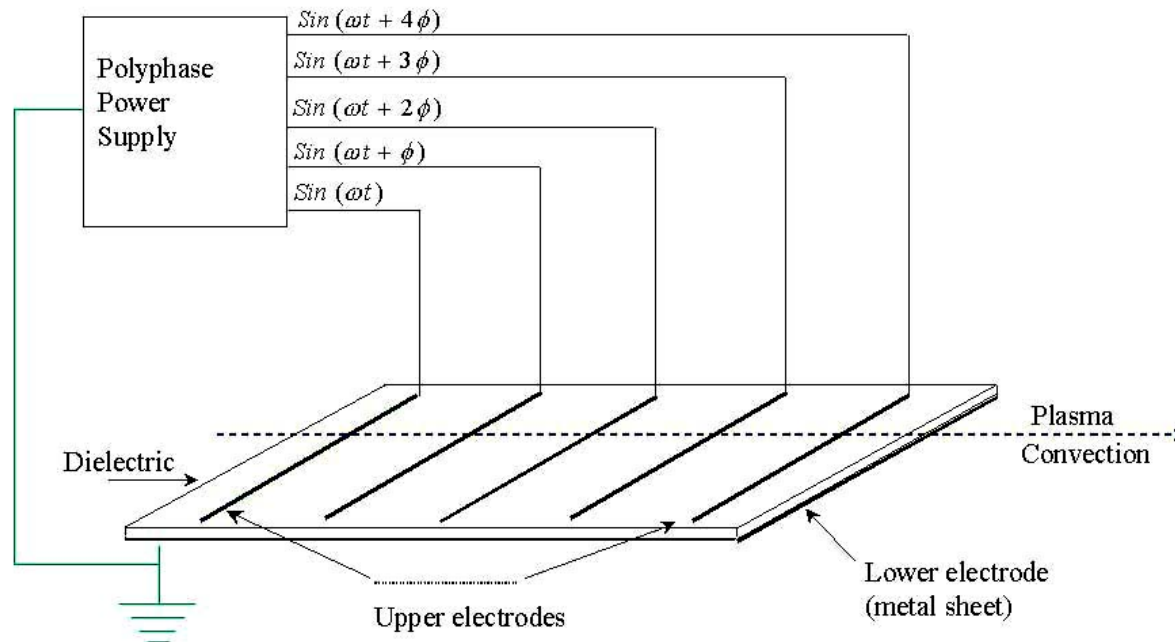


Length = 0,92 m, Span Width = 0,85 m, Wing Area  $A=0,5 \text{ m}^2$



# Unsteady Lift and Propulsion Using Electrokinetic Wave Propulsion

Possible Fixed-Wing Simulation (Bionic Transformation) of Mechanical Wave Propulsion Through Waving („Flapping“) Travelling Electrostatic Soliton-Fields.



Peristaltic Plasma-Pumping with travelling electrostatic waves (Source: Karakaya et al.)

- Plasma Speeds up to 100 m/s achievable.
- Today's MAVs operate with maximum 25 m/s.

Is the Development of an All Electrokinetically Propelled Micro-Aerial Vehicle Possible?

# First Steps to All Electrokinetic MAV Propulsion



First Lifter Experiments at the

Institute of Bionics and Evolutionstechnique,  
TU Berlin 2002

See also video:

<http://www.bionik.tu-berlin.de/user/goeksel/lifter3.avi>

# First Steps to All Electrokinetic MAV Propulsion

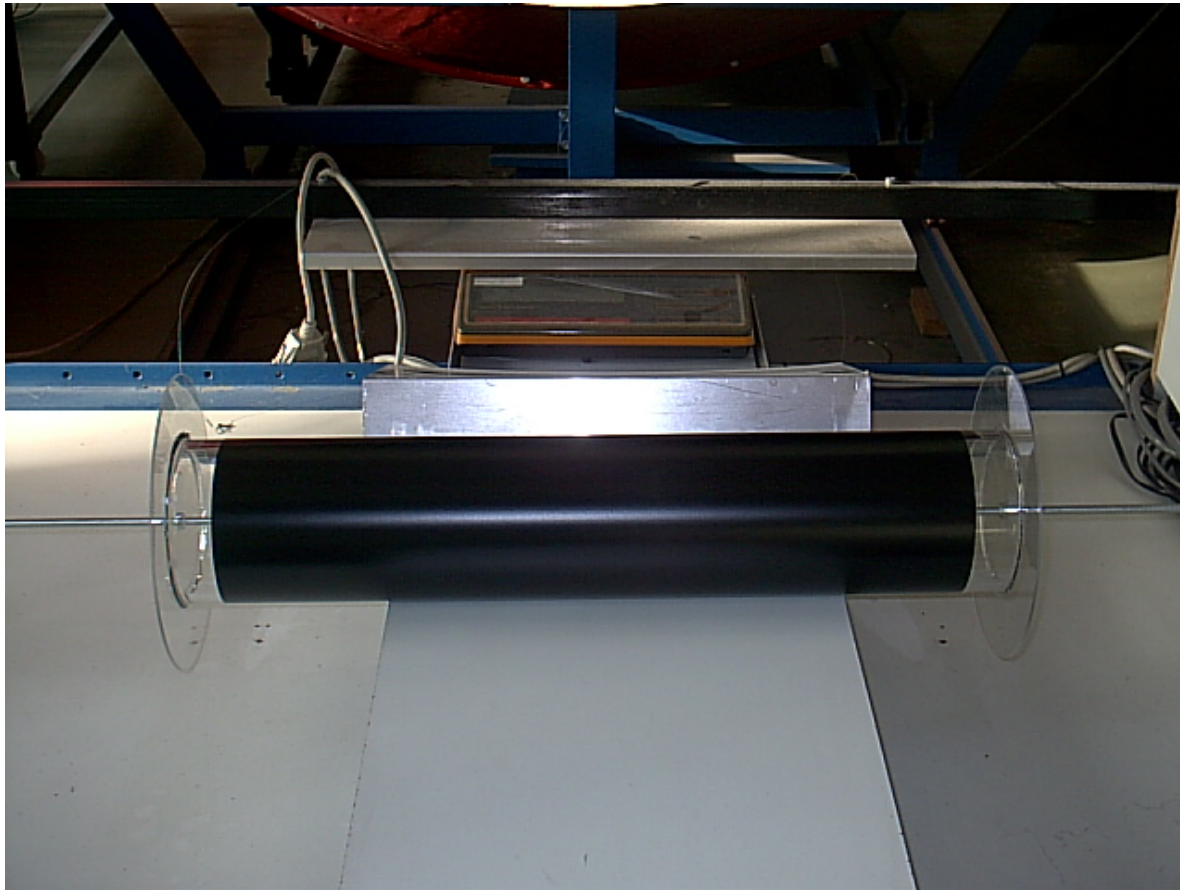


University of Alabama Huntsville: <http://www.eb.uah.edu/ipt/previouspages/2001.htm>

The *Patrocinor* uses a completely silent ionic propulsion system powered by the next generation of fuel cells. An exoskeleton framework has sensors imbedded into it and is comprised of layers of radar reducing and high strength materials.

See also paper: **AIAA 2001-3433** Paper - Unmanned Air Ground Vehicle (pdf)

# Electroaerodynamic Coanda Effect – Cylinder Wake Flow Control



Experiments to Active Cylinder Wake Flow Control Using Electric Field Actuators  
at the Institut of Bionics and Evolutionstechnique, Technical University of Berlin

# Further Applications in Rotational Flows

- New NASA Goals for „**Smart Efficient Components**“  
(see <http://www.grc.nasa.gov/WWW/AERO/base/sec.htm>)

Demonstrate Plasma Glow Discharge Device for LPT Flow Control (09/01)  
Demonstrated operation of a plasma glow discharge device in relevant LPT flow environment

- Research at the University of Notre Dame  
(see <http://www.nd.edu/~ame/facultystaff/Corke,Thomas.html>)

## **Separation Control for Rotocraft using a Glow-Discharge Flat Array**

This involves the development of a "flat-array plasma actuator" as an unsteady electrostatic pump which is designed to energize the low momentum fluid in a separated flow and cause reattachment. This has the advantages of having a very high frequency band-width, high energy density, and no moving parts. The applications for this are primarily directed towards helicopter which includes: suppressing advancing stall of rotors. Controlling flow separations on multifaced surfaces which are designed for a low radar (stealth) signature, and controlling separations in bends of internal air-inlet flows.

# Literature

[1] Mueller, T.J. (ed), *Fixed and Flapping Wing Aerodynamics for Micro Air Vehicle Applications*, Progress in Aeronautics and Astronautics Volume 195, AIAA Publishing, Reston, VA, 2001.

[2] Goeksel, B. (2002) Active Flow Control to Improve the Flight Performance of Micro Aerial Vehicles. DGLR-Fachausschuss-Sitzung „Unbemannte Flugzeuge – Einsatzmöglichkeiten, Flugleistungen und Flugeigenschaften“  
DLR Braunschweig (in German).

[3] Karakaya, F.; Sherman, D. M.; Roth, J. R. (1999) A Polyphase Low Frequency RF Power Supply for a One Atmosphere Uniform Glow Discharge Plasma (OAUGDP). *26<sup>th</sup> International Conference on Plasma Science (ICOPS 99)*, Paper 3P35, Monterey, CA .

[4] Selig, M.; Lyon, C.; Giguere, P.; Ninham, C.; and Guglielmo, J. *Summary of Low Speed Airfoil Data*, Vol. 2, SoarTech Publ., Virginia Beach, VA, 1996.

[5] AGARD, *Low Reynolds Number Vehicles* , AGARDograph AG-288, 1985.